

# eRD1: EIC Calorimeter Development

S. Ali, E. Aschenauer, V. Berdnikov, S. Boose, M. Carmignotto, A. Denisov, L. Dunkelberger, A. Durum, S. Fazio, Y. Fisyak, D. Griggs, A. Hernandez, T. Horn, H.Z. Huang, J. Huang, G. Hull, W. Jacobs, M. Josselin, Y. Kim, K. Landry, L. Leon, I. Pegg, M. Purschke, A. Kiselev, E. Kistenev, S. Kuleshov, C. Lauer, C. Munoz-Camacho, H. Mkrtchyan, C. Pinkenberg, S. Roustom, E. Rozas, H. San, M. Sergeeva, A. Sickles, S. Stoll, V. Tadevosyan, S. Trentalange, R. Trotta, P. Ulloa, A. Vargas, G. Visser, R. Wang, S. Wissink, C. Woody, L. Zhang, R. Zhu

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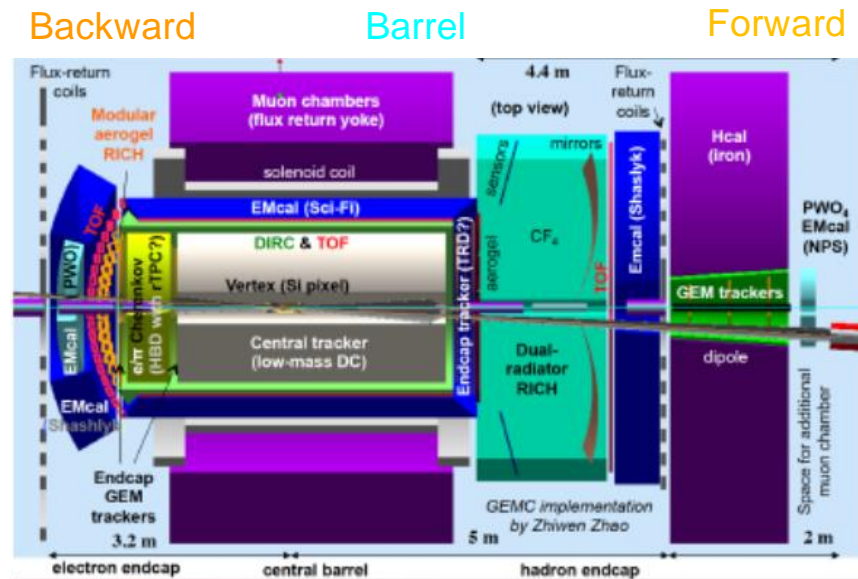


# Goals of the Consortium

Develop calorimeters that meet the requirements of physics measurements at an EIC – including all regions of the detector

Systematic uncertainties are expected to be the main limiting factor in extracting the underlying physics

- ❑ **Reduce systematic uncertainty** on a broad range of physics measurements by employing **different technologies**
- ❑ Broaden the spectrum to include **new technologies** that could potentially offer **improved performance, lower cost, mitigate risk and broaden user involvement**



$\eta$	Nom enclosure	Tracking		Electrons		HCAL
		Resolution	Allow e d X/X <sub>y</sub>	Resolution $\sigma_E/E$	Resolution $\sigma_E/E$	
-6.9-5.8	Auxiliary Detectors	low -Q2 tagger				
...		Instrumentation to separate charged				
-4.5-4.0	Backwards Detectors	$\sigma_E/p \sim 0.1\% p+2.0\%$		(1.0-1.5)%/√E+0.5%		
-4.0-3.5		$\sigma_E/p \sim 0.05\% p+1.0\%$		7%/√E		
-3.5-3.0	Central Detector	$\sigma_E/p \sim 0.05\% p+0.5\%$		$\sigma_{Ee} \sim 20\mu\text{m}$ $d_2(z) - d_1(z)$ $\sim 20/p_T \text{ GeV}$ $\mu\text{m} + 5\mu\text{m}$		
-3.0-2.5		$\sigma_E/p \sim 0.05\% p+1.0\%$		(10-12)%/√E		
-2.5-2.0	Forward Detectors	$\sigma_E/p \sim 0.05\% p+1.0\%$				
-2.0-1.5		$\sigma_E/p \sim 0.1\% p+2.0\%$		(1.0-1.5)%/√E+0.5%		
-1.5-1.0	Instrumentation to separate charged					
-1.0-0.5						
-0.5-0.0	Auxiliary detectors					
0.0-0.5						
0.5-1.0	Proton Spectrometer					
1.0-1.5						
1.5-2.0	Proton Spectrometer					
2.0-2.5						
2.5-3.0	Proton Spectrometer					
3.0-3.5						
3.5-4.0	Proton Spectrometer					
4.0-4.5						
...	Proton Spectrometer					
>6.2						

# eRD1: Near Term Activities

## ❑ Central and/or mid-rapidity region

- Tungsten Calorimeter R&D at [UCLA](#)
- Tungsten Calorimeter R&D at [BNL \(sPHENIX\)](#)

→ [See talk by Oleg Tsai](#)

Focus for FY18

Expect to complete by  
end of FY18

## ❑ Electron and Ion Endcaps

- R&D on Crystal Calorimeters – [CUA](#), [IPNO](#), JLab, ANSL, BNL, Caltech
  - address calorimeter resolution performance (systematic uncertainty) like: variations of crystal quality, choice of photosensors, and shower reconstruction (need prototype)

→ [Next slides in this talk](#)

Expect to complete by  
end of FY19/20,  
pending availability of  
funding

# eRD1: Next Steps

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## ❑ Central and/or mid-rapidity region

- Tungsten Calorimeter R&D at [UCLA](#)
- Tungsten Calorimeter R&D at [BNL \(sPHENIX\)](#)

## ❑ **Electron and Ion Endcaps**

Focus for FY19/20

- R&D on Crystal Calorimeters – [CUA](#), [IPNO](#), JLab, ANSL, BNL, Caltech
  - Optimization of geometry, cooling, choices of readout

# Broadening the Technology Spectrum

An effective way to reduce systematic uncertainties is to combine data from multiple complementary detectors with critical components exhibiting different behavior.

*EIC will have at least two such detectors (Temple U. Meeting 2017)*

- ❑ Improved energy and timing resolution in the central region for measuring jets and providing particle ID for SIDIS and DVCS
  - R&D on High Resolution Tungsten Shashlik Calorimeter – UTFSM, MEPHI
- ❑ Alternative active calorimeter material that are more cost effective and easier to manufacture than, e.g. crystals
  - R&D on scintillating glass and/or ceramics – small business/CUA
- ❑ Other calorimeter technologies
  - Investigation of suppressing the slow component in  $\text{BaF}_2$
  - Hadronic calorimetry with integrated timing - UCLA
- ❑ Data acquisition systems
  - Trigger-less readout – INFN

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# eRD1: Path Forward

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- ❑ ***Encourage new efforts at a minimum critical level***
- ❑ ***Seek other funding sources*** through alternative mechanisms ***after initial phase***, such as institutional support, other agency support, LDRD, SBIR, etc.

# Crystal Calorimeter R&D for EIC (part of eRD1)

Salina Ali, Vladimir Berdnikov, Marco Carmignotto, Dannie Griggs, Tanja Horn, Giulia Hull, Michael Josselin, Ian Pegg, Martin Purschke, Casey Lauer, Carlos Munoz-Camacho, Hamlet Mkrtchyan, Salim Roustom, Ho San, Sean Stoll, Vardan Tadevosyan, Richard Trotta, Andres Vargas, Rong Wang, Craig Woody, Renyuan Zhu

*A.I. Alikhanyan National Science Laboratory/Yerevan, Catholic University of America, The  
Vitreous State Laboratory, Institut de Physique Nucleaire d'Orsay/France, Jefferson Laboratory,  
Brookhaven National Laboratory, Caltech*

THE  
CATHOLIC UNIVERSITY  
of AMERICA



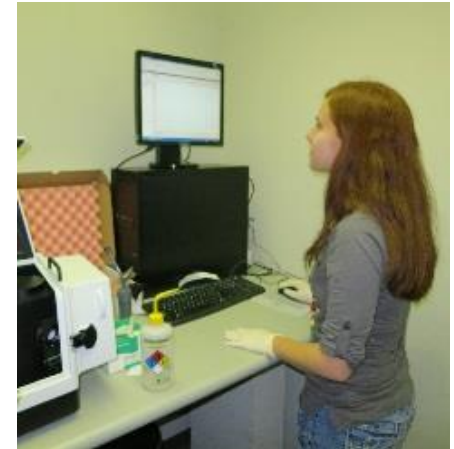
Jefferson Lab  
Thomas Jefferson National Accelerator Facility



BROOKHAVEN  
NATIONAL LABORATORY

# Students

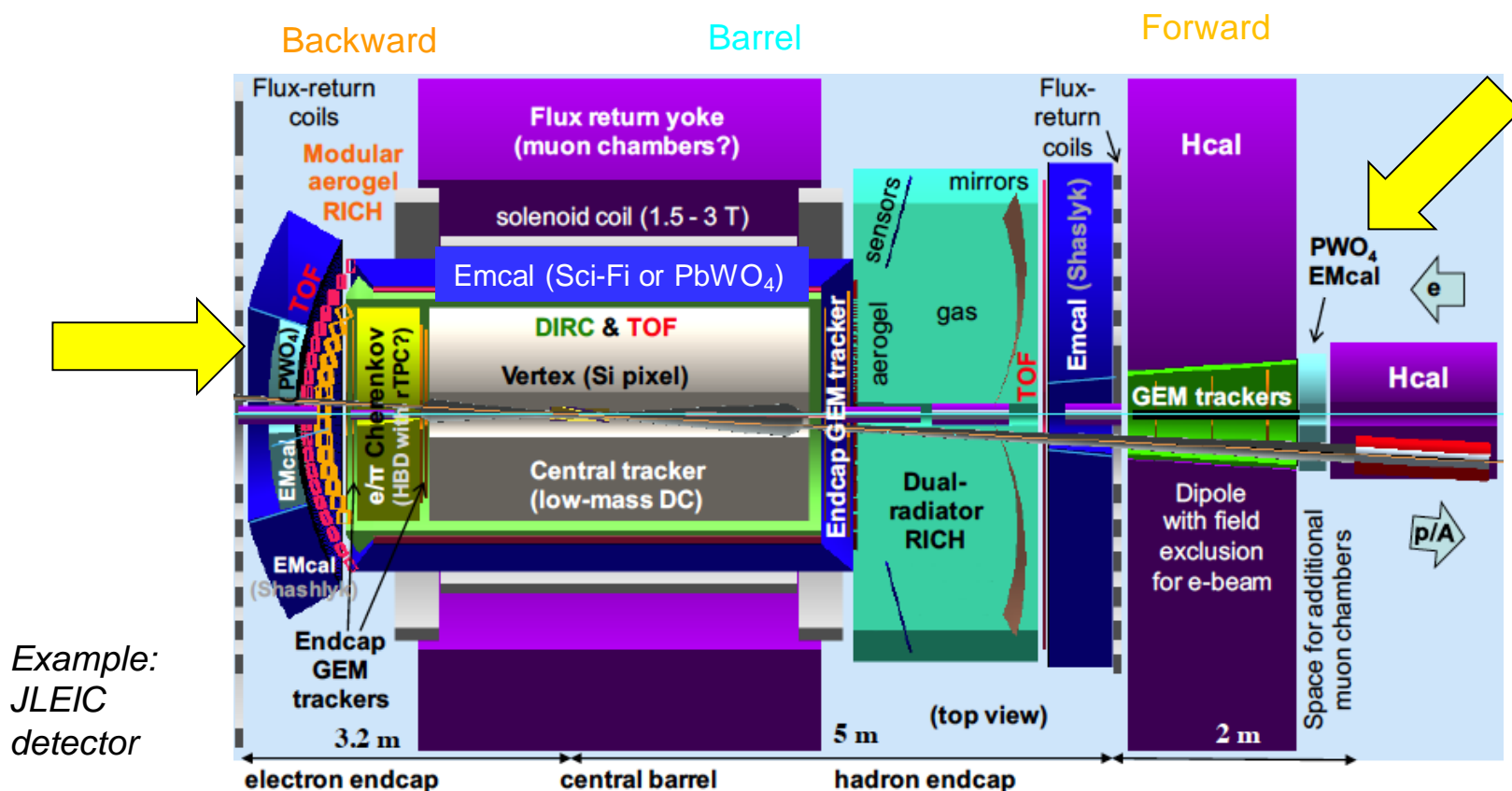
- Dannie Griggs (Marshall High school)
- Abby McShane (Marshall High school)
- Salim Roustom (Marshall High school)
- Christian Runyon (Trinity High School)
- Casey Lauer (Marshall High School)
- Frederic Georges (IPN-Orsay)
- Salina Ali (CUA)
- Richard Trotta (CUA)
- Andres Vargas (CUA)
- Marco Carmignotto (CUA)
- Ho San (IPN-Orsay)



# High resolution calorimetry for endcaps

- ❑ **PID requirements in the electron endcap** primarily driven by nearly real photo-production and semi-inclusive and exclusive processes
- ❑ **PID requirements in the ion endcap** primarily driven by exclusive processes, e.g., DVCS ( $\gamma$  vs. photons from  $\pi^0$  decay) and to detect excitation in recoil baryons

*Detection at very small angle is needed*



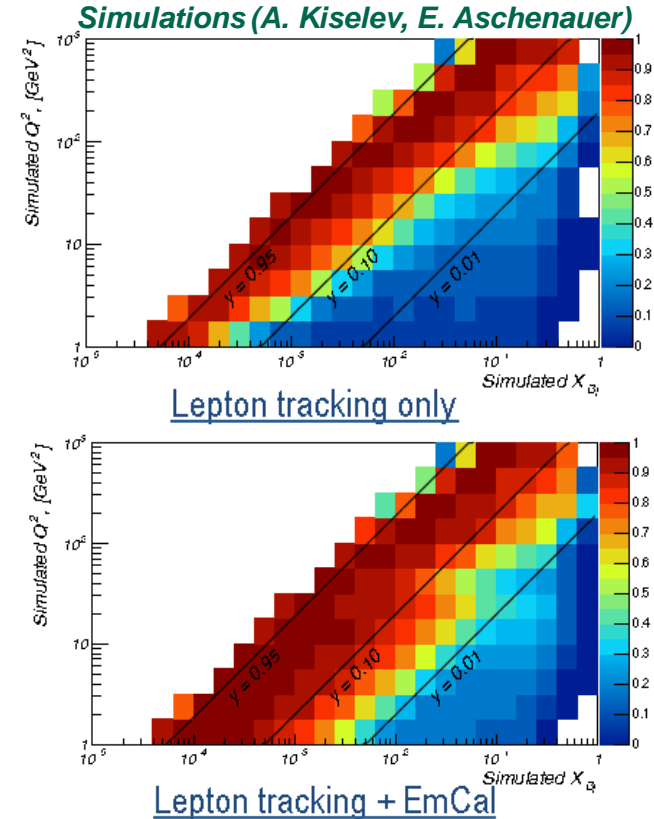
# High resolution calorimetry – functions and requirements

## ❑ EM calorimetry has two main functions

- **Particle Identification:** important for discriminating single photons from, e.g.,  $\pi^0$  decay and  $e/p$
- **Particle Reconstruction:** driven by need to accurately reconstruct the four-momentum of scattered electrons at small angles, where the momentum (or energy) resolution from the tracker is poor.

## ❑ EM Inner Calorimeter Requirements

- Good resolution in angle to *at least 1 degree* to distinguish between clusters
- Energy resolution  $(1-1.5\%)/\sqrt{E} + 0.5\%$  for measurements of cluster energy
  - Resolution helps to extend useful y-range, “purity” in  $x/Q^2$  bins
- Time resolution to  $< 2ns$
- Ability to withstand radiation down to at least 1 degree wrt beam line



# What was planned for FY18

## **Crystal characterization for specifications and impact on EIC detector performance**

- Characterize, including chemical analysis, 300-400 SICCAS crystals produced in 2017 in collaboration with NPS project
- Evaluate influence of crystal surface properties
- Evaluate CRYTUR later growth cycle crystals

## **Prototype to establish limiting energy and position resolution, and, together with simulations, to evaluate options to reduce the constant term**

- Construct prototype assuming suitable number of crystals is available
- Calibrate prototype with tagged photon beam at JLab
- Together with simulations evaluate uniformity of crystal response and statistical fluctuations of containment losses

## **Investigation of different readout systems and influence on resolution**

- PMTs may be a viable option since not directly in magnetic field
- Evaluate photodiode readout options and long term stability

# What was achieved in FY18 – to date

*With commitment of internal university and laboratory funds and through synergy with the NPS project at JLab we made progress even within constrained FY17 budgets*

## **Crystal characterization for specifications and impact on EIC detector performance**

- ❖ Procured components and allocated space for crystal characterization at both CUA and IPN-Orsay
- ❖ Established a non-destructive sampling method for chemical composition analysis
- ❖ Performed chemical composition and surface analysis, and tested the optical properties of 120/320 crystals produced at SICCAS in 2017 that were procured through synergy with the VSL and the NPS project
- ❖ Provided feedback to vendors and iterating on reaching required crystal properties and quality, e.g. by “compensation” of the crystal surface.

## **Prototype construction to establish limiting resolution**

- ❖ Some work towards NPS prototype, no work on EIC prototype

## **Investigation of different readout systems and influence on resolution**

# Plans for FY18 - remainder

**Complete goals from previous FY17 and also try to make progress beyond that as budget constraints allow**

- ❑ ***Procure and test, in collaboration with the NPS project, rectangular crystals from SICCAS (460 purchased) and CRYTUR (anticipate 450 crystals)***
  - ❑ Continue crystal characterization including optical, chemical composition and surface studies for additional samples
  - ❑ Measure radiation hardness of crystals and investigate correlations with chemical composition
  - ❑ Iterate with vendors on crystal requirements and composition optimization, e.g. surface and chemical composition
- ❑ ***Construct a prototype to test if actual crystal performance is suitable for EIC***
- ❑ To make progress beyond attempt to continue studies of readout options.

## IPN-Orsay (France) – proximity to Giessen U. and CRYTUR

### ❑ Optical Transmittance (L/T)

- Fiber-based spectrometer

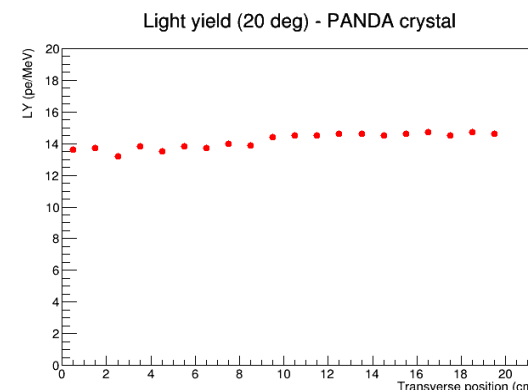
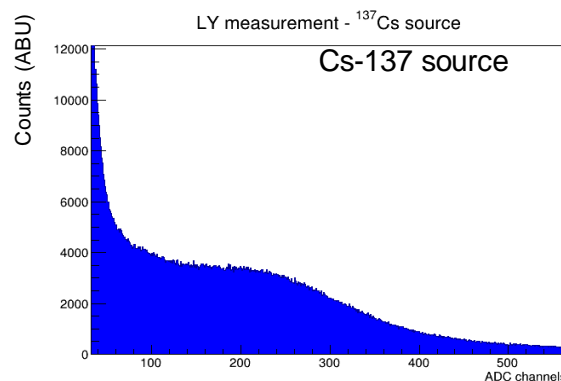
### ❑ Radiation Hardness

- Strong  $^{60}\text{Co}$  sources available at LCP-Orsay
- ALTO facility can provide 50 MeV electrons up to  $1\mu\text{A}$ . A Proton beam (Tandem) is also available



### ❑ Crystal light yield and timing

- *Cross check with subset of crystals previously tested at CUA, Giessen and Caltech ongoing*



# Infrastructure for crystal testing - *completed*

## CUA (USA) – proximity to JLab

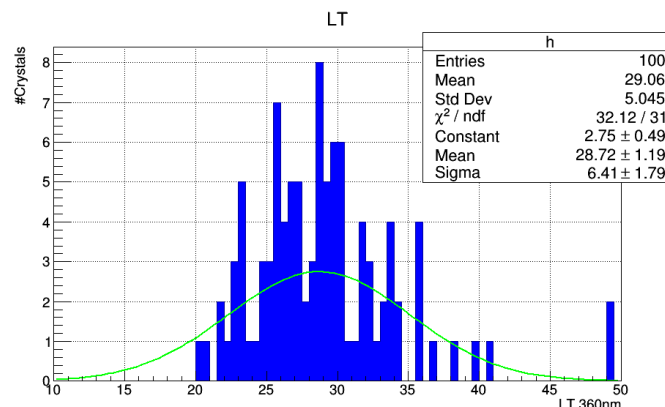
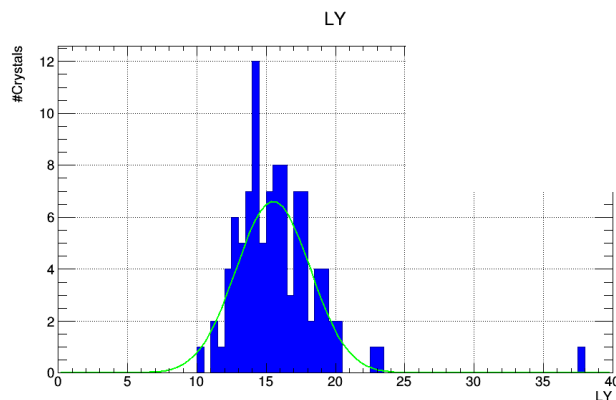
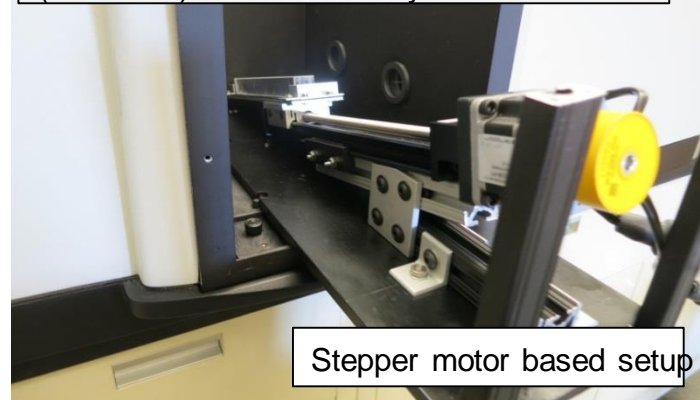
### ❑ Optical Transmittance (L/T)

- 86% of SICCAS 2017 crystal subset passes at 420nm, only 10% at 360nm
- 5% of crystals passing specification have mechanical flaws that impact uniformity of light collection

### ❑ Crystal light yield and timing

- 55% (55/100) of SICCAS 2017 and ~50% (1/2) of Crytur crystals pass specs, ***discussion with vendors about role of mechanical flaws, roughness and chemical composition in (controlled) increasing LY***
- Crytur higher crystallization crystals not suitable for NPS requirements

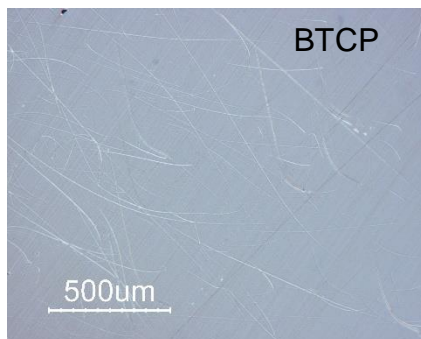
Spectrophotometer with integrating sphere (NSF MRI) in dedicated crystal lab



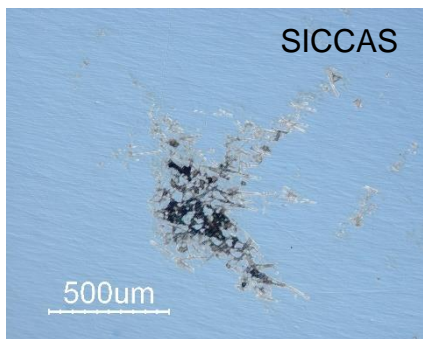
SICCAS 2017 crystals: Large variations in light yield and optical transmittance

# Crystal Quality: *Surface Analysis*

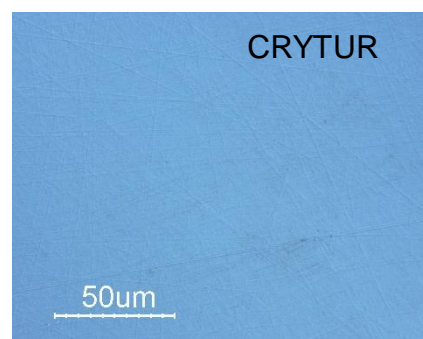
## ❑ Typical crystal surface quality



Out-of-business



Mass production may be available  
– 320 crystals delivered in 2017



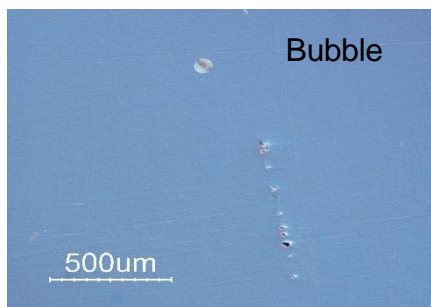
Mass production uncertain



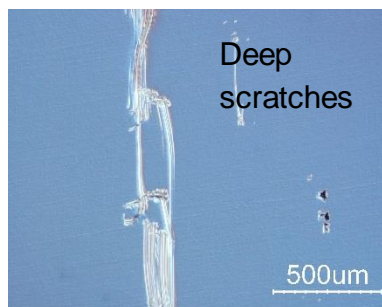
Measurements:  
scanning microscope  
in collaboration with  
VSL

- Scratches applied in a well-defined manner may benefit crystal properties – discussion with vendors ongoing

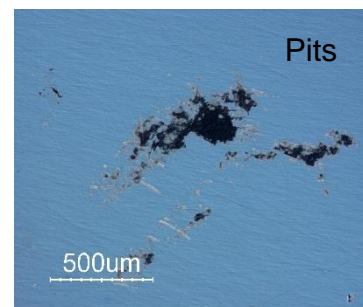
## ❑ Looking deeper into defects: SICCAS 2017 crystals



Bubble



Deep  
scratches



Pits

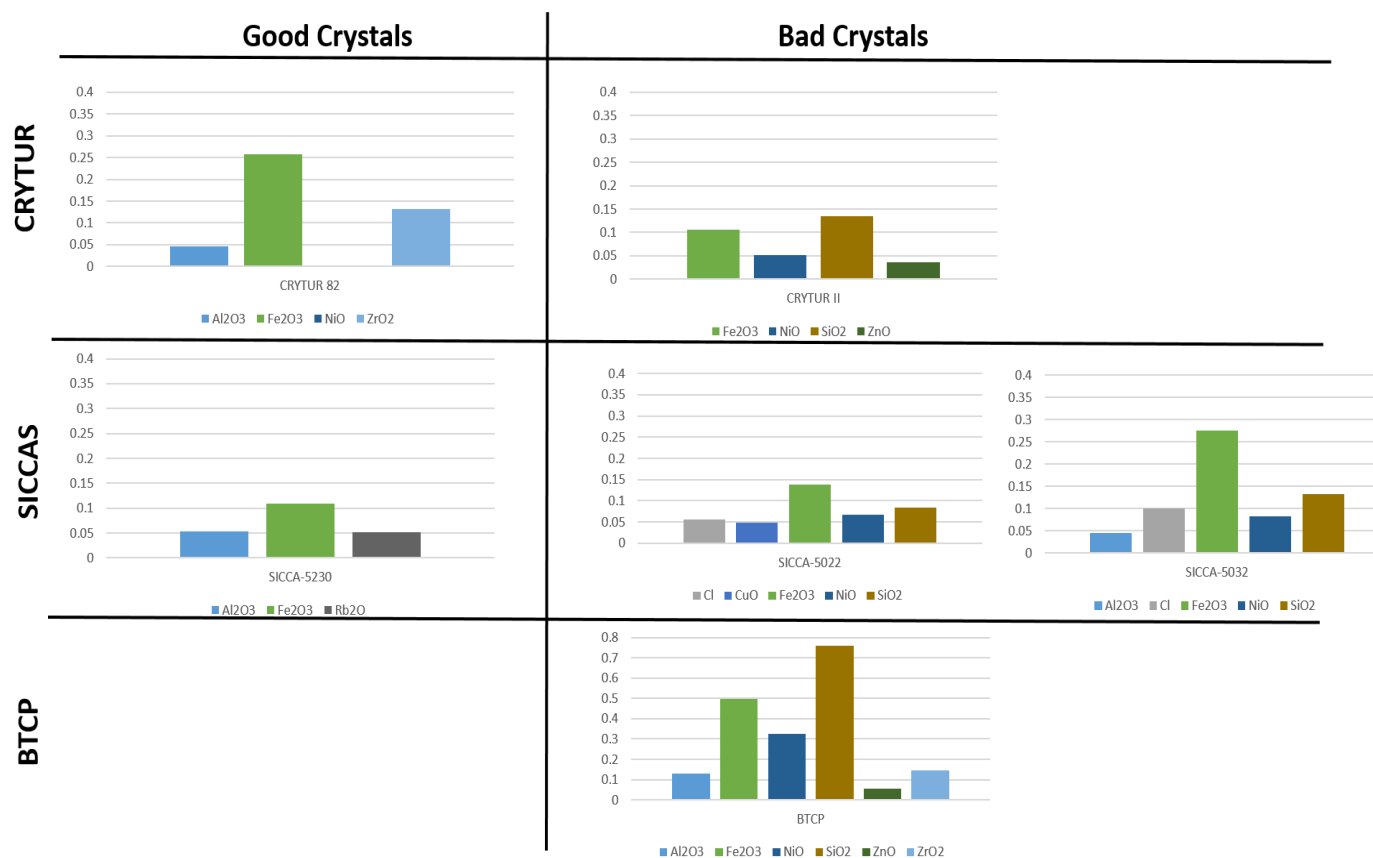
Anticipate 450 crystals  
from CRYTUR in  
collaboration with NPS  
project for testing

- Defects result in high, but non-uniform light yield – discussion with vendors about mitigation ongoing

# Crystal Quality: *Chemical Composition*

- ❑ Developed non-destructive sampling method
- ❑ XRF of 10-15% of 100 SICCAS 2017 crystals in collaboration with VSL

## Overview of variation in chemical composition



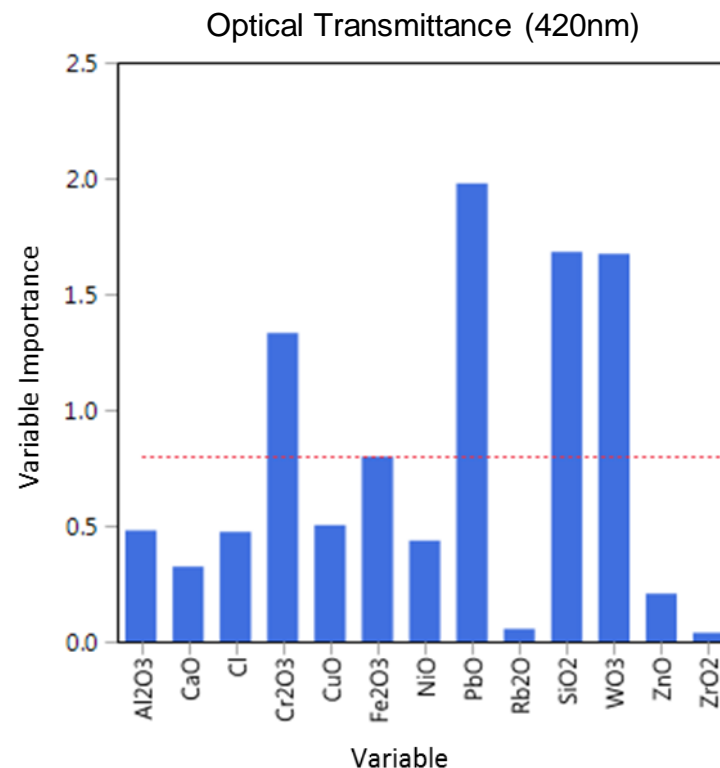
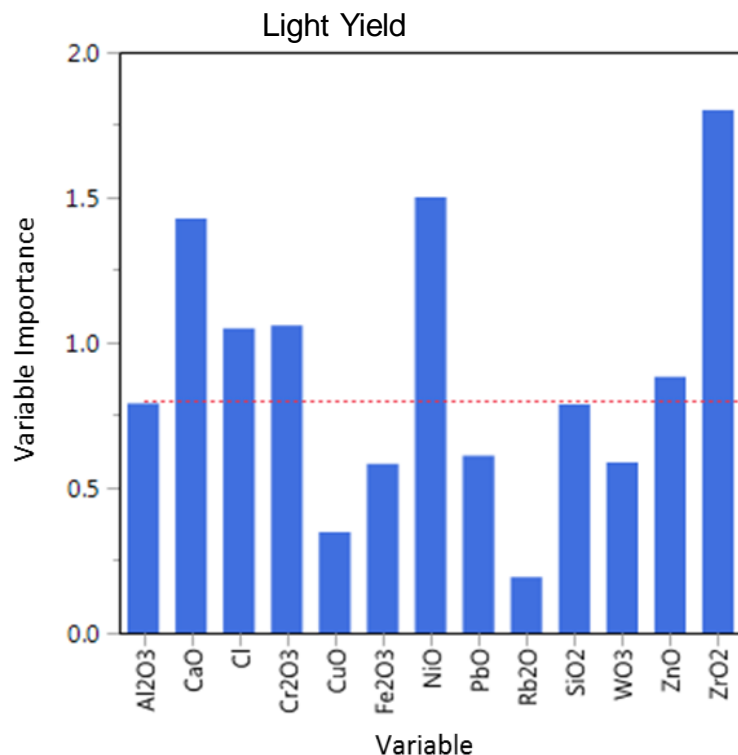
# Correlations: chemical composition and optical properties

- ❑ Importance of variation in lead and tungsten, as well as other elements on crystal optical properties determined by statistical analysis
- ❑ For stoichiometry used a multivariate approach, in which correlations are estimated by a pairwise method
  - Clear dependence of transmittance (420nm) on stoichiometry, light yield does not seem to depend on it

	Al2O3	CaO	Cl	Cr2O3	CuO	Fe2O3	NiO	PbO	Rb2O	SiO2	WO3	ZnO	ZrO2	Light Yield	LT 420
Al2O3	1.0000	-0.0637	0.0500	0.0222	-0.5035	0.6193	-0.1994	0.2246	0.1136	-0.4142	-0.3617	0.2726	0.2487	0.2094	-0.1775
CaO	-0.0637	1.0000	-0.1947	-0.0910	-0.0910	-0.2581	-0.3309	-0.0255	-0.0910	-0.1440	0.2046	-0.1271	-0.2315	-0.3779	-0.1202
Cl	0.0500	-0.1947	1.0000	-0.1337	0.2209	0.4481	0.6386	0.0721	-0.1337	-0.0945	-0.3613	-0.1868	0.0636	-0.2777	-0.1756
Cr2O3	0.0222	-0.0910	-0.1337	1.0000	-0.0625	0.0620	0.3061	0.3970	-0.0625	-0.2357	-0.3078	-0.0873	-0.1590	-0.2804	-0.4934
CuO	-0.5035	-0.0910	0.2209	-0.0625	1.0000	-0.1440	0.2086	0.2237	-0.0625	0.0827	-0.1630	-0.0873	-0.1590	-0.0919	-0.1861
Fe2O3	0.6193	-0.2581	0.4481	0.0620	-0.1440	1.0000	0.1952	0.4125	-0.2305	-0.4911	-0.7115	0.3980	0.4512	-0.1540	-0.2958
NiO	-0.1994	-0.3309	0.6386	0.3061	0.2086	0.1952	1.0000	0.1406	-0.2273	-0.0730	-0.2637	-0.1491	-0.3345	-0.3974	-0.1615
PbO	0.2246	-0.0255	0.0721	0.3970	0.2237	0.4125	0.1406	1.0000	-0.0700	-0.4356	-0.8960	0.3456	-0.0146	-0.1618	-0.7324
Rb2O	0.1136	-0.0910	-0.1337	-0.0625	-0.0625	-0.2305	-0.2273	-0.0700	1.0000	-0.2357	0.2155	-0.0873	-0.1590	0.0512	0.0207
SiO2	-0.4142	-0.1440	-0.0945	-0.2357	0.0827	-0.4911	-0.0730	-0.4356	-0.2357	1.0000	0.3862	-0.0763	-0.1999	0.2082	0.6228
WO3	-0.3617	0.2046	-0.3613	-0.3078	-0.1630	-0.7115	-0.2637	-0.8960	0.2155	0.3862	1.0000	-0.4071	-0.2302	0.1556	0.6197
ZnO	0.2726	-0.1271	-0.1868	-0.0873	-0.0873	0.3980	-0.1491	0.3456	-0.0873	-0.0763	-0.4071	1.0000	0.1292	-0.2337	0.0767
ZrO2	0.2487	-0.2315	0.0636	-0.1590	-0.1590	0.4512	-0.3345	-0.0146	-0.1590	-0.1999	-0.2302	0.1292	1.0000	0.4764	-0.0142
Light Yield	0.2094	-0.3779	-0.2777	-0.2804	-0.0919	-0.1540	-0.3974	-0.1618	0.0512	0.2082	0.1556	-0.2337	0.4764	1.0000	0.1931
LT 420	-0.1775	-0.1202	-0.1756	-0.4934	-0.1861	-0.2958	-0.1615	-0.7324	0.0207	0.6228	0.6197	0.0767	-0.0142	0.1931	1.0000

# Correlations: chemical composition and optical properties

- ❑ To assess the impact of individual chemical components, correlation models were constructed using partial least squares



## ❑ Next steps:

- Radiation hardness
- Additional crystal samples – so far focused on samples that failed at least one optical specification

# Critical Issues and Path Forward

- ❑ Crystal characterization and iteration with vendors is critical to produce  $\text{PbWO}_4$  crystals suitable for EIC
  - ❑ Optical, chemical composition and surface studies
  - ❑ Prototyping for actual crystal performance
- ❑ Expect to test 460 crystals from SICCAS and 450 crystals from CRYTUR this year. Funding for resources in FY19 would expedite progress
- ❑ Future progress: choice of readout, cooling, geometry
  - uniformity, control of systematics



# Budget Request FY2018

Item	FY18 (\$)	FY19 (\$)
Procure crystals from Crytur	30k	10k
Technical Support	21k	18k
Parts for prototype and construction	38k	
Travel	28k	28k
Parts for cooling system		38k
Parts for readout system	31k	32k
<b>TOTAL</b>	<b>148k</b>	126k

- ❑ **20% cut:** delay construction and testing of the prototype, continue crystal characterization studies but at lower efficiency and our general studies of different readout options . This limited continuation, even with a 20% cut, is enabled with the majority of our activities funded by the NPS project and internal funds.
- ❑ **40% cut:** Our focus would shift towards the NPS project, which would be the funding source for our activities, and we may only provide information relevant specifically for EIC. We would attempt to continue our general studies of different readout options at lower efficiency. These would proceed at significantly reduced efficiency regarding EIC. Construction and testing of the prototype is delayed.

# External Funding

- ❑ All of the FTEs required for working towards finalizing the crystal test setup and crystal characterization are provided by CUA/IPNO or external grants. The absence of any labor costs makes this proposed R&D effort extremely cost effective.
  - Nine people working on project – additional collaborators at JLab, Giessen University, Yerevan, VSL@CUA
- ❑ The 2014 and 2015 SIC crystals are provided through synergistic activities with independent research for the Neutral Particle Spectrometer (NPS) project at JLab.
- ❑ The expertise and use of specialized instruments required for crystal characterization and their chemical analysis, as well as additional crystals samples are made possible through collaboration with the Vitreous State Laboratory (VSL) at CUA that is also collaborating on the NPS project.
- ❑ Similarly, the work highly benefits from support groups within IPN Orsay and the expertise provided by Giessen University.

# Publications and Talks

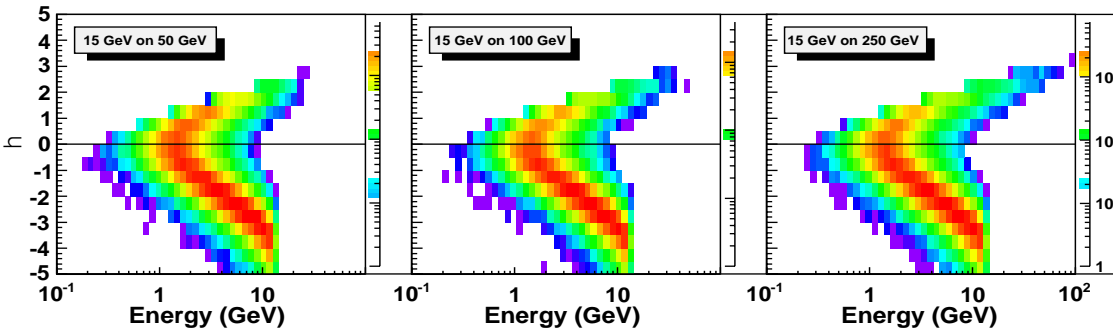
- C. Munoz-Camacho et al.. “R&D for high resolution calorimetry at the future Electron-Ion Collider”, Presentation at the XVIIth International Conference on Calorimetry in Particle Physics, 15-20 May 2016, Daegu, South Korea
- R. Trotta et al. “*Exclusive reactions and the PbWO<sub>4</sub>-based Inner Calorimeter for the Electron-Ion Collider*” presentation at the APS April 2017 meeting, Washington, DC
- T. Horn, C. Munoz-Camacho, C. Keppel, I. Strakovsky et al., arXiv:1704.00816 (2017) “*Workshop on High-Intensity Photon Sources (HIPS2017) Mini-Proceedings*”
- T. Horn et al., J.Phys. Conf. Ser. **587** (2015) 1, 012048 “*A PbWO<sub>4</sub>-based Neutral Particle Spectrometer in Hall C at 12 GeV JLab*”
- T. Horn et al. “*Physics Opportunities with the Neutral Particle Spectrometer in Hall C*”, presentation at the APS DNP 2015 Fall meeting, Santa Fe, NM

# Example: Exclusive Reactions - DVCS

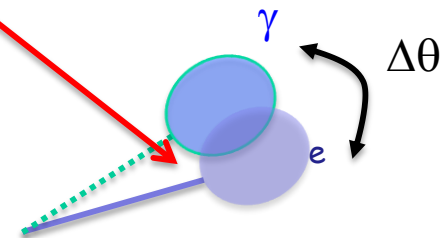
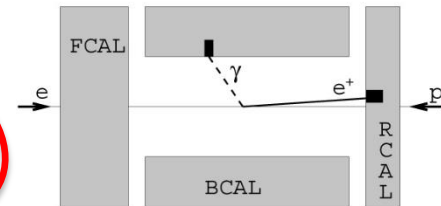
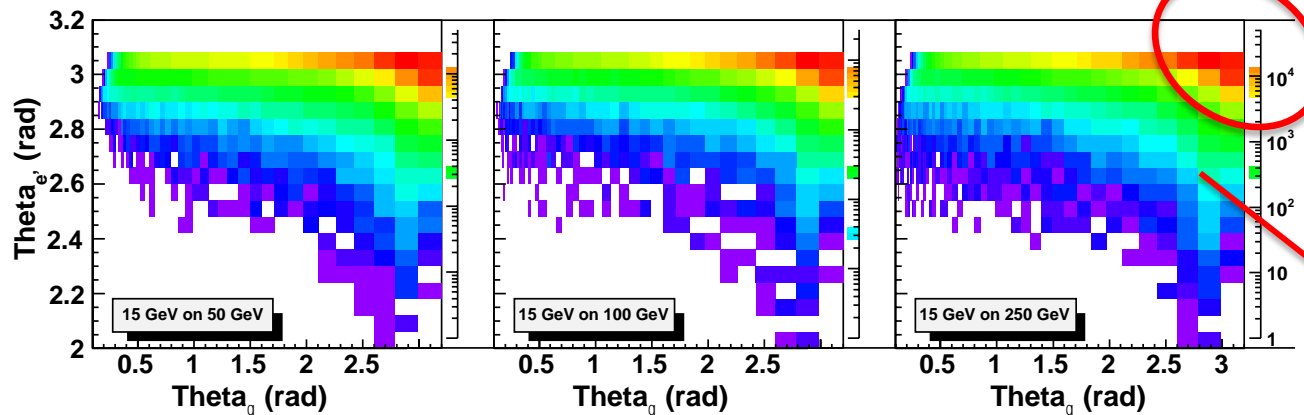
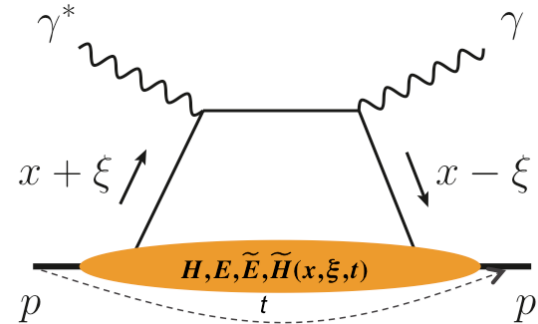
## DVCS – photon kinematics:

Slide from E. Aschenauer, EIC UG meeting Jan. 2016

Cuts:  $Q^2 > 1 \text{ GeV}$ ,  $0.01 < y < 0.85$



increasing Hadron Beam Energy influences max. photon energy at fixed  $\eta$  photons are boosted to negative rapidities (lepton direction)



**ECal granularity:** need to be able to distinguish clusters down to  $\Delta\theta = 1^\circ$